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Radioactive Fallout from Terrorist Nuclear Detonations

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Abstract

Responding correctly during the first hour after a terrorist nuclear detonation is the key to reducing casualties from a low-yield surface burst, and a correct response requires an understanding of the rapidly changing dose rate from fallout. This report provides an empirical formula for dose rate as a function of time and location that can guide the response to an unexpected nuclear detonation. At least one post-detonation radiation measurement is required if the yield and other characteristics of the detonation are unknown.

Introduction

Radioactive fallout in the age of nuclear terrorism presents a threat that is very different from the cold war fallout threat in both character and magnitude. In the event of a nuclear exchange with the Soviet Union, the expected large number of high yield near-surface detonations would have covered large areas of the United States with radioactive fallout that remained lethal for days and a threat to health for much longer. This was the motivation for the fallout shelter programs of the 1960s in which shelters with large fallout protection factors were identified or constructed, and equipped with provisions for many days.

Only a single or perhaps a small number of nuclear detonations could be staged by terrorists, and the yield of each of them is likely to be 10 to 100-fold lower than the yield of Soviet strategic weapons. Hence the total amount of radioactive fallout from a terrorist nuclear attack would likely be at least three orders of magnitude less than that from a nuclear exchange with the Soviet Union, and it would threaten a much smaller fraction of the American population.

The character of the fallout hazard from a terrorist nuclear detonation is also very different from cold war expectations: The lethal fallout plume is much smaller, extending only a few tens of miles downwind with a width of a couple miles, depending on wind conditions, and the acute lethal radiation dose occurs entirely within the first few hours. Time dependent dose rates are required to support a rapid response to a terrorist nuclear detonation. This report provides a model for the time dependence and applies it to the problem of an unexpected nuclear detonation.

Current Predictions

The current tools for radioactive fallout prediction, such as the widely used HPAC software [1] and the NARAC facility [2] at Lawrence Livermore National Laboratory, provide ground-shine fallout dose contours as an overlay on a map. Typically the highest

level contour shows where the radiation dose to an unprotected person during the first 24 hours would be lethal to at least 50% of the population. Other contours may indicate the onset of injury, observable medical effects, etc. A typical fallout prediction from NARAC is shown in Fig. 1 along with the predicted areas for death and injury from prompt effects (blast, heat, and nuclear radiation). Delayed effects such as fires may also be important, but they are not shown in the figure. NARAC takes radioactive fallout predictions from the KDFOC3 code [3], which is based on fallout data from nuclear tests at the Nevada Test Site.

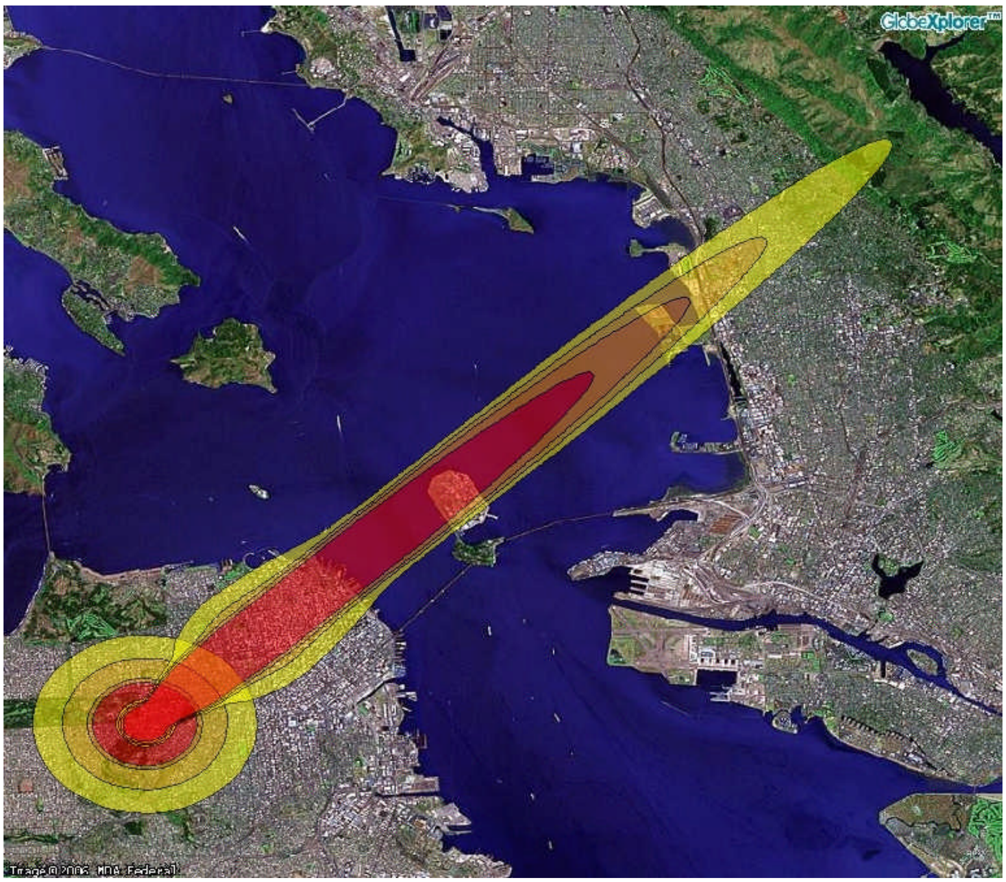

Fig. 1. Fallout plume as predicted by NARAC for a 10-kt surface burst in San Francisco with 5-mph winds from the southwest. Contours (in order of smallest to largest) indicate fatalities in over 50% of the population, fatalities in over 10% of the population, non-fatal injuries in over 50% of the surviving population, and non-fatal injuries in over 10% of the surviving population. The circles centered on ground zero indicate the corresponding regions for prompt effects.

As shown in Fig. 1, the fallout hazard will likely cover a larger area and could cause more casualties than the prompt effects. (The exception is an air burst such as the Hiroshima and Nagasaki detonations, for which the local radioactive fallout is minimal.)

For the 10-kt surface burst shown in Fig. 1, and using a population distribution map for the San Francisco Bay region, 33,000 fatalities are expected from prompt effects and 137,000 from radioactive fallout (assuming 24 hours of unprotected exposure). In this example the fallout plume covers a densely populated area of San Francisco as well as the unpopulated bay. The casualty figures could be very different for different winds or detonation locations.

Although the radioactive fallout plume extends far downwind from ground zero, it is narrow and covers only a small fraction of a large metropolitan area such as the San Francisco Bay region. Hence the vast majority of the regional population is in no danger and should take no action. For those who are in danger, there is little that can be done to escape the prompt effects if a nuclear detonation is unexpected. However it is possible to survive the radioactive fallout if action is taken before the accumulation of a lethal dose. This is the basis for the concept of selective evacuation and shelter in which only those at risk need to evacuate or take shelter, and they need to move only a few miles [4].

Note that the fallout plume of Fig. 1, which we have taken as an example for analysis in this report, has a narrow cigar shape because there is no directional wind shear. (The absence of directional wind shear is not a common occurrence.) The calculation does include vertical wind shear (i.e., greater wind velocity at higher altitude) but there is no change in wind direction with altitude. Directional wind shear can produce broad irregularly shaped fallout patterns, but the total radioactivity deposited is determined by the nuclear yield and other characteristics of the detonation. (See further discussion of wind shear below.)

Dose Rate

Current predictions of integrated dose contours such as the example above show where the radioactive fallout will go, but dose rate and its time dependence are the key to saving lives in the event of a terrorist nuclear detonation. We have used special NARAC output options to obtain dose rate vs. time at two representative locations for the example above, one at the San Francisco shoreline and the other at the Berkeley shoreline. Both locations are on the centerline of the fallout plume. As shown in Fig. 2, fallout at the San Francisco shoreline arrives earlier and is much more intense than in Berkeley. Predictions for 5 and 15-mph winds are shown.

For the 5-mph southwest wind, fallout does not arrive at the San Francisco shoreline for almost an hour after detonation, but the lethal dose of about 400 Rad is then accumulated within roughly one hour after arrival for an unprotected person. Clearly, people in this area must not wait to respond or they will become casualties. However, if they leave the fallout area quickly or take shelter in a location with a large fallout protection factor for a few hours, they can completely escape serious injury. Those who are farther downwind have more time to react and receive a less intense radiation dose. However most of the 24-hour integrated dose still occurs within the first few hours after fallout arrival. Dose rate curves such as those in Fig. 2 can be produced for any location. They provide the full time dependence of the radiation hazard.

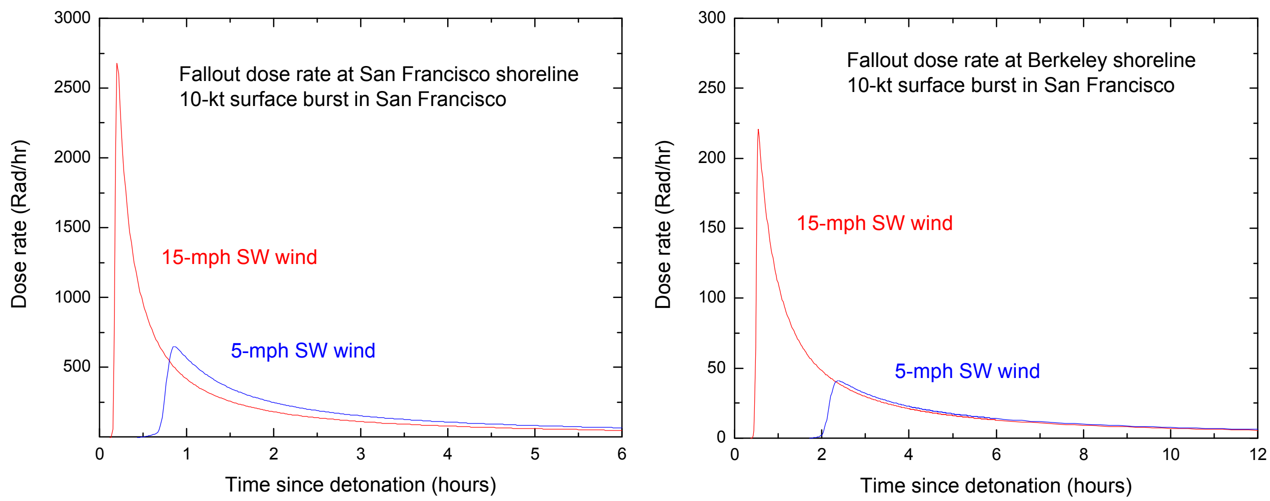

Fig. 2. Radiation dose rate from fallout for different wind velocities and locations. Note the 10-fold difference in the vertical scale for the two locations.

Parameterization of Fallout Dose Rate

We have found that the spatial distribution and time dependence of the dose rate from radioactive fallout can be represented by simple functions with a small number of free parameters that depend on the circumstances of the detonation. These parameters can be determined from a fit to a sophisticated fallout model (e.g., NARAC with KDFOC3) if the circumstances of the detonation are known, or they can be determined from local weather and immediate measurements of actual fallout if the circumstances are unknown. In what follows we discuss the parameterization of a cigar-shaped plume as illustrated by the example above.

Time Dependence

The curves in Fig. 2 are extremely well fit by a function of the form

$$I(t) = \frac{I_0\, t^{-1.2}}{1 + e^{-(t-t_A)/\sigma}} \qquad \text{Rad / hour} \tag{1}$$

where $I(t)$ is the dose rate or intensity of the radiation in Rad/hour, t is the time since detonation in hours, and I_0, t_A, and σ are adjustable parameters. The "initial" intensity I_0 corresponds to what is often called the effective dose rate at H + 1 hour, t_A is the fallout arrival time, and σ is the spread in arrival time (i.e., the duration of the fallout precipitation). After deposition, the decay of the fission product gamma radiation intensity follows the well established $t^{-1.2}$ power law. With the parameter values shown

in Tables I and II, the function of Eq. 1 fits the NARAC calculation to within the width of the lines in Fig. 2. In the tables, r is the distance from the detonation point.

Table I. 5-mph wind

location	r (km)	I_0 (Rad/hr)	t_A (hr)	σ (hr)
San Francisco	6.5	572	0.77	0.03
Berkeley	18.0	120	2.18	0.06

Table II. 15-mph wind

location	r (km)	I_0 (Rad/hr)	t_A (hr)	σ (hr)
San Francisco	6.5	417	0.18	0.008
Berkeley	18.0	111	0.50	0.015

Distance Dependence

Equation 1 provides an excellent fit to the time dependent dose rate at the two chosen locations. Now we extend the fit to the full area of fallout risk, first by determining the dependence of the three centerline fit parameters on distance from the detonation point, and next by adding the variation of dose rate perpendicular to the centerline. We expect the arrival time to be proportional to distance and inversely proportional to wind velocity. For the 5-mph NARAC data, $t_A \approx r / 8.2$ km/hr. The spread in arrival time is so small that it is unimportant for response planning. However it increases with distance and can be approximated by $\sigma \approx 0.0026\, r + 0.013$ hr for the 5-mph data.

The effective H +1 hour dose rate I_0 has a more complicated dependence on distance. It is affected by the circumstances of the detonation such as the yield and emplacement, which affects the particle size distribution of the radioactive fission products. We used the fallout distribution as calculated by NARAC to find an approximation to the distance dependence of I_0:

$$I_0(r) = \frac{Y_0}{(a+r)^b} \qquad \text{Rad / hour} \qquad (2)$$

where $Y_0 = 3.59 \times 10^4$, $a = 2.5$, and $b = 1.9$ for the 5-mph NARAC data. This parameterization is compared to the NARAC calculation in Fig. 3. The comparison time of 4 hours is well after the arrival time at all locations so that fallout deposition is complete.

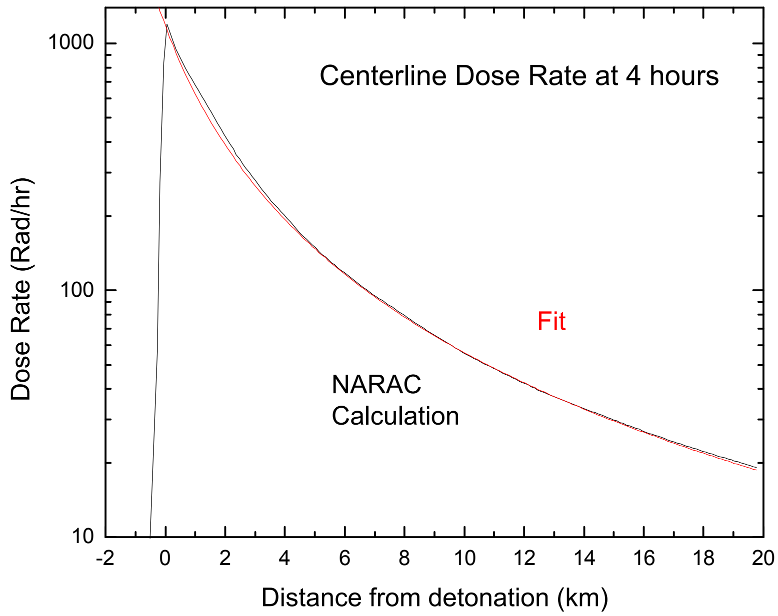

Fig. 3. Comparison of the NARAC calculation and the fit along the plume centerline for a 5-mph wind.

Plume Width

We have found an approximation for the transverse profile of the dose rate in the fallout plume and compared it to NARAC calculations at three different distances. The approximation, normalized to 1 on the plume centerline is

$$f(w) = A\,e^{-\left(\frac{w}{\delta}\right)^2} + B\,e^{-\left[\frac{w}{\Delta}+\left(\frac{w}{c}\right)^4\right]} \tag{3}$$

where w is the perpendicular distance from the plume centerline in km, and A, B, δ, Δ, and c are fit parameters. The fit parameters depend on distance, with most of the variation being in the Gaussian width δ. The NARAC calculation of the plume width is shown at three distances in Fig. 4 and compared to the fit (Eq. 3).

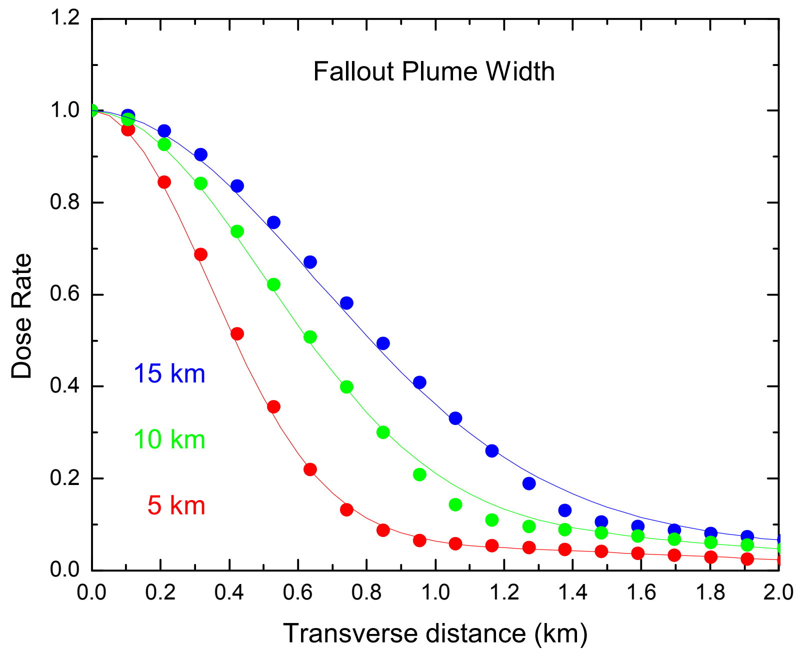

Fig. 4. Comparison of the NARAC calculation of fallout plume width for a 5-mph wind (solid points) and the fit (solid lines) at the indicated down-wind distances from the detonation point.

Dose Rate Map

We can now use our empirical model to generate maps of the spatial and time dependence of the dose rate from radioactive fallout. This information is not a usual output from current fallout models, but it is essential for the characterization of the fallout hazard from a terrorist nuclear detonation. The fallout dose rate as a function of location and time is given by the product of $I(t, r)$ (Eq. 1) and $\mathrm{f}(w, r)$ (Eq. 3). (The r dependence is implicit through the dependence of the fit parameters on r.) We have used our dose rate model to generate a movie for the example of Fig. 1, a 10-kt surface detonation in San Francisco with 5-mph southwest winds. Two frames from the dose rate movie are shown in Fig. 5. The most intense dose rate contour corresponds to 3000 Rad / hr or greater, which produces a lethal dose within 10 minutes. Note that the dose rate parameterization does not apply upwind of ground zero and overestimates the width near ground zero. The empirical model can also generate dose rate vs time plots such as those in Fig. 2 for any location.

Other fallout patterns

Turbulent weather or winds that change direction with altitude can produce fallout patterns that differ from the cigar-shaped pattern considered here. (Variation of winds with time is less important because of the limited time interval of interest here.) These patterns may be wider or bifurcate into two (or more) lobes. We expect that a parameterization of these fallout patterns would require a different width function (wider

or with two peaks), but expect that the time and distance dependence would be similar to that given here. Fitting irregular fallout patterns is beyond the scope of the present work.

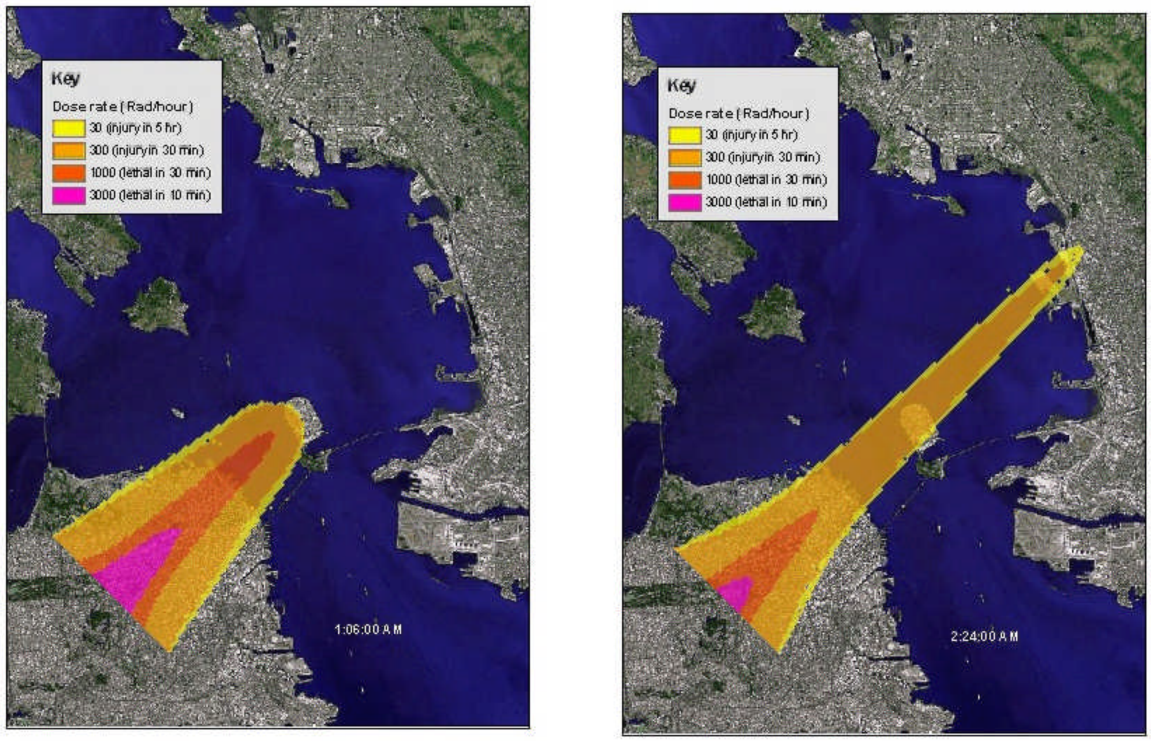

Fig. 5. Dose rate maps from the fitting function at 1 hour (left) and 2.5 hour (right) after detonation for the event shown in Fig. 1.

Response to a Nuclear Event

We have pointed out the importance of considering dose rate and its time dependence rather than 24-hour integrated dose in responding to the radioactive fallout hazard from a nuclear explosion, and we have provided a model for the dose rate based on empirical formulas that are easily evaluated. Unfortunately, all fallout prediction tools will be ineffective in the immediate aftermath of an unexpected nuclear detonation because much of the information that determines the fallout distribution (e.g., yield, device design, and emplacement conditions) will be unavailable. This information may not be known until it is too late to save people from fallout exposure, and some of the information may never be known. Even if the fallout hazard cannot be predicted because of unknown initial conditions, it may be that an empirical model such as the one presented here can be calibrated from immediate measurements and used to guide response.

Immediate Measurements

The agreement of our empirical model with sophisticated fallout calculations such as those performed by NARAC is extremely good, in fact the agreement is much better than the accuracy of the sophisticated calculations. (A discussion of the large uncertainties in fallout prediction is beyond the scope of the present report.) However our empirical model contains multiple fitting parameters. How can a model with multiple undetermined parameters be of use in the response to a nuclear detonation? Surprisingly, even a single measurement, and certainly a few measurements of an actual fallout radiation dose rate are sufficient to calibrate the model for event response.

The width function $f(w)$ contains several fitting parameters in order to match the non-Gaussian tail of the NARAC width distribution. However the fallout plume for the example analyzed here is so narrow that an accurate measure of its width is not critical for event response. Furthermore, the plume width is relatively insensitive to the detonation conditions. Hence, in the absence of directional wind shear, the width profiles from the example in this report could be used as is for event response. (See the remarks below on alternate profiles.)

What information would be available within a few minutes of an unexpected nuclear detonation? The location would be obvious from prompt destruction, and wind information would be available from real time weather data. This would permit an immediate prediction of the fallout plume direction and centerline. The wind speed determines the arrival time $t_A(r)$ at different downwind ranges. The one important piece of missing information is $I_0(r)$, the H + 1 hour dose rate and its dependence on distance. $I_0(r)$ depends on the unknown distribution of radioactivity with respect to particle size, which in turn depends on the unknown conditions of device emplacement, height of burst, and yield. $I_0(r)$ also depends on the (known) wind velocity. Example calculations such as those presented here provide a good guess at the functional form of $I_0(r)$ (see Fig. 3) so that even a single measurement of fallout dose rate at a known distance could provide the overall normalization and enable reliable guidance for event response. Two or more measurements would pin down the range dependence of $I_0(r)$.

What could an individual with no access to empirical models, NARAC output, or official instructions do for himself and those around him in the aftermath of a nuclear detonation? From the formula for radiation decay $I(t) = I_0\, t^{-1.2}$, and a guess at the fallout arrival time, the past and future radiation dose at any location can be determined from a single radiation measurement at that location at any time after fallout arrival. Hence any responder with a radiation meter, even with a complete absence of fallout predictions, can know what dose people at that location have already received and what dose they will get in the future.

Future Work

We have studied examples of fallout plumes with different wind velocities but no directional wind shear. Upper level winds blowing in a different direction from surface

winds are common. They will have the greatest effect on fallout patterns at large distance from ground zero because of the time required for fallout particles to rise to high altitude and fall back down. However even the early time fallout within roughly 20 km of ground zero, which is the subject of the present analysis, is affected by upper level winds. Hence a broader set of wind conditions should be studied to improve the empirical model and obtain ready-to-use formulas. One possibility is to replace the plume-width shape derived here with a selection of precalculated cookie cutter or "keyhole" shapes, one for each of several different weather patterns.

Conclusions

Reducing casualties from an unexpected (terrorist) nuclear detonation requires knowledge of the time dependence of the radiation dose rate from fallout and an understanding of what it means. We have developed a model for fallout dose rate that can be quickly calibrated with immediate measurements and used to guide nuclear event response. The radiation dose rate from fallout changes very rapidly during the first few hours after detonation, a critical effect that is not apparent from standard predictions and is not included in current response planning. People in danger of fallout exposure need to respond within an hour or less, but most of those who respond correctly can escape death and injury.

Acknowledgements

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